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Status and Recent Results for EMSP Project #70108

Effects of Fluid Distribution on Measured Properties for Partially Saturated, Shallow Subsurface Conditions

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Effects of Fluid Distribution on Measured Geophysical Properties for Partially Saturated, Shallow Subsurface Conditions

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Introduction

Our objective is to improve geophysical imaging of the vadose zone by developing improved methods for interpreting geophysical field data. The purpose of this EMSP project is to develop relationships between laboratory measured geophysical properties and porosity, saturation, soil composition, and fluid distribution, for partially saturated soils. Algorithms for relationships between soil composition, fluids, and geophysical measurements can provide new methods to interpret geophysical field data collected in the vadose zone at sites such as Hanford, WA.

This project is a continuation of EMSP project 55411, Joint Inversion of Geophysical Data for Site Characterization and Restoration Monitoring. The final report for that project and annual reports for project 70108 are available on the EMSP web site at http://emsp.em.doe.gov/. Papers and reports for these projects are also available at the URL http://www.llnl.gov/ees/esd/expgeoph/Berge/EMSP/publications.html or at the URL http://www.llnl.gov/tid/lof/ (perform a search on author name). Results of this work have been presented at the FY2001 Vadose Zone Workshop that was held at PNNL in November, 2000, and at the Subsurface Contaminants Focus Area Midyear Review 2001 held in Atlanta, GA, in March, 2001. Recent publications are listed at the end of this report.

For EMSP project 70108, we modified the laboratory apparatus that was built for ultrasonic velocity measurements in EMSP project 55411, so that we could make velocity measurements for partially-saturated soil samples as well as for wet and dry samples. We measured compressional and shear wave velocities in various soil samples at pressures equivalent to the top few meters of the subsurface, examining effects of fluids, clay content, organic content (peat), microstructure, and pressure. We further examined microstructural effects by using the DOE Advanced Photon Source at Argonne National Laboratory to perform x-ray computed tomography imaging for some sand samples.

After making velocity measurements, we analyzed the data to find relationships between measured geophysical properties and parameters of interest for hydrology or site characterization, such as fluid distribution, saturation, porosity, clay content, soil type. In the analysis, we use both rock physics theories and empirical approaches. In addition, we are developing algorithms for inverting velocities to obtain information such as soil type.

Summary of Results

Recent published results from this project are listed at the end of this report. Here we briefly summarize some main results.

Laboratory measurements of dry sand and sand/clay samples as functions of pressure and packing show that loosely-packed samples have very steep compressional-wave velocity (Vp) gradients for pressures equivalent to the top 3-5 m of the subsurface. For more tightly-packed samples, the Vp gradient is less steep, and all the pure sand samples have similar velocities for pressures below the top 2 m. Our laboratory results explain seismic velocities measured *in situ* for beach sands in the top 2 m of the subsurface (Bachrach and Nur, 1998; Bachrach et al., 1998), where Vp in a seismic refraction survey was found to have low values, steep gradients, and to depend greatly on shot-receiver distances for loose sands above the water table.

Ultrasonic measurements for dry sand-clay samples show that Vp and shear-wave velocity (Vs) both vary with clay content as well as with packing and pressure. As for pure sands, packing is most important for pressures equivalent to the top 2 m of the subsurface, and not important for pressures equivalent to 3 m depth or deeper. Figure 1 shows velocity vs. clay content for dry sand-clay samples at about 0.1 MPa (about 5 m depth). The bottom part of the figure represents key features of the microstructure, with circles for sand grains and dark regions for clay. Although Vs decreases monitonically with increasing clay content, Vp initially increases as clay cements sand grains and fills dry pores. Vp then decreases with increasing clay content when the amount of clay is sufficient to form a continuous clay matrix through the sample. Similar behavior has been observed for sand-clay mixtures at 10 to 50 MPa pressures (Marion et al., 1992). Our data show that Poisson's ratio and the Vp/Vs ratios depend strongly on clay content but are not greatly dependent on pressure in the top few m of the subsurface. Vp/Vs values for samples with small amounts of clay are about 1.6 to 2.2, and values are near 2.5 for samples with large amounts of clay. Poisson's ratio is near 0.4 for samples containing large amounts of clay.

Our measurements for partially-saturated sand samples showed that the velocities, frequencies, and wave amplitudes depend strongly on saturation and on relative pressures of the pore fluid and applied pressure. Decreasing the pore pressure by about 10 percent increased the shear wave amplitude and Vp and Vs slightly because of better grain-grain contact in the sample. Decreasing the pore pressure by about 20 percent significantly reduced frequencies, Vs, and shear wave amplitudes, because of poor grain-grain contact in that case. For low pressures equivalent to the top few meters of the subsurface, capillary pressures in sands can be of the same order as pore fluid and confining pressures. This can lead to fluctuations in velocity and changes in microstructure with small changes in saturation. We also found that samples close to full saturation but containing a few air bubbles exhibited behavior associated with patchy saturation. We are using rock physics theories to model velocities of our samples, and to investigate fluid distribution effects.

These results corroborate Vp and Vs velocities, Vp/Vs estimates, and velocity gradients observed in shallow seismic reflection and refraction surveys in the literature (e.g., Birkelo et al., 1987; Bachrach et al., 1998; Carr et al., 1998). Borehole and seismic reflection data found steep gradients and Vs values about 200 to 400 m/s in the top 25 m for glacial till, with Vp/Vs near 3.6 and Vs near 450 m/s below 25 m (Carr et al., 1998). Vp values for Arkansas River sands in the top 3 m of the subsurface were found to be about 250 m/s in a shallow reflection survey (Birkelo et al., 1987), and frequency changed with changes in saturation in the vadose zone.

We developed an algorithm to invert Vp and Vs data together to obtain soil composition information and tested it for several examples using synthetic field data derived from our laboratory measurements with added random noise of about 10 to 20 percent. Our results show that for a layered model with interbedded sands, silty sands, and sandy clays, the lithology can be reconstructed from the velocities if both Vp and Vs data are available. We are working on incorporating electrical properties data in the inversion, to provide an additional independent constraint.

Collaborations and Networking with Other Researchers and Gov't. Agencies

The P.I. for this project was a participant in the Non-invasive Characterization Work Group for the DOE Complex-Wide Vadose Zone Science and Technology Roadmap for Characterization, Modeling and Simulation of Subsurface Contaminant Fate and Transport. Insights gained in this project and resulting advancements in the area of petrophysics (relating geophysical measurements to hydrological properties and soil composition) were used when developing the roadmap. The California Dept. of Water Resources has expressed interest in our laboratory measurements of ultrasonic velocities in soils, for comparison to their field measurements of shallow soil properties in regions where they are performing seismic hazards assessments. The ultrasonic velocity results also have generated a lot of interest from university researchers, particularly from individuals working on seismic field experiments for measuring velocities in the shallow subsurface. Our lab measurements provide the first direct corroboration of very low velocities seen in field data for the top few meters of the subsurface (e.g., Birkelo et al., 1987; Bachrach et al., 1998). We have communicated our results to Don Steeples of the University of Kansas and Mike Waddell of the University of South Carolina, for assistance in interpretation of the field seismic data that they have collected at DOE sites as part of their EMSP and EM SCFA projects. We are also networking with other current and former EMSP project P.I.'s (e.g., C. Carrigan, LLNL, E. Majer, LBL, J. Geller, LBL, D. Steeples, U. Kansas, R.J. Knight, Stanford/U. British Columbia) to plan possible future collaborations on field experiments to test the lab and theory results of this EMSP project. The project P.I.'s visited Stanford U. recently to speak to R. J. Knight and the result was that we wrote a paper with Stanford researchers, for a book chapter in a Society of Exploration Geophysicists publication that is likely to be used widely in the environmental consulting industry and at universities to train the next generation of near-surface geophysicists. The project P.I.'s also visited LBL recently to find out about their capabilities in the area of measuring seismic properties of soils. The project P.I.'s attended the recent annual meeting of the Society of Exploration Geophysicists and took part in a poster session on near-surface geophysics. This session included D. Steeples. M. Waddell also attended the meeting and had discussions with the project P.I.'s. The lead P.I. on this project is the session chair for the Petrophysics Session at the upcoming annual meeting of the Engineering and Environmental Geophysical Society. This meeting is the main place where geophysical consulting firms in the environmental cleanup business learn about recent scientific advances. Many of these firms are DOE subcontractors who do work at contaminated sites.

Implications for Vadose Zone Characterization and Monitoring

Our results have shown that compressional and shear-wave velocity data can be used to obtain information about fluids, clay content, and structural changes with depth, particularly when laboratory data are available for callibration of field seismic data and when both compressional and shear-wave velocities are available. Our laboratory measurements corroborate many features observed in recent field studies, including steep gradients and low velocities in the shallow subsurface and strong dependence of velocities and frequencies on fluid distribution and microstructural factors. This suggests that combining lab and field data may be a powerful method for improving seismic imaging of the vadose zone, for characterization and cleanup monitoring. We also recommend that modeling be done before designing field seismic experiments, in order to optimize receiver spacing and overall design, as well as to assess effects of steep velocity gradients and signal attenuation.

FY02 Research and Future Plans

We will continue to analyze the laboratory ultrasonic data using rock physics theories, and develop additional relationships between geophysical parameters, fluids, and soil types. We also will continue to develop algorithms for inverting geophysical data to obtain soil and fluid distribution information. Currently we are working on ways to include electrical properties data. If needed, we will make a few more laboratory ultrasonic measurements on natural soils and partially-saturated sands.

Our results will be presented in scientific conferences, in papers for journals such as *Geophysics* or the *Journal of the Engineering and Environmental Geophysical Society*, and in a final project report for EMSP at the end of FY02.

We believe the logical continuation of this research would be to do a field seismic test at a well-characterized site in a convenient location, followed by more extensive tests at more complex sites. In particular, we are looking into the possibility of collaborating with LLNL and LBL researchers on a future project to collect and interpret shallow seismic data at clean and contaminated sites, possibly at LLNL. This could be accomplished by submitting a proposal to a future EMSP call for applied research proposals, or through some other type of EM funding for research and development to further the work begun in the EMSP projects.

Recent Publications

Berryman, J. G., Berge, P. A., and Bonner, B. P., 2001, Estimating rock porosity and fluid saturation using only seismic velocities: LLNL report UCRL-JC-135507, Geophysics, in press.

Bertete-Aguirre, H., and Berge, P. A., 2001, Recovering soil distributions from seismic data using laboratory velocity measurements: LLNL report UCRL-JC-141559, submitted to the Journal of Environmental and Engineering Geophysics.

Zimmer, M., Prasad, M., Bonner, B. P., and Berge, P. A., 2001, Measurement of velocity and attenuation in shallow soils: submitted to be included as a chapter in Near-Surface Geophysics, Applications and Case Histories, Vol. II, Butler, D. K., ed., Society of Exploration Geophysicists, Tulsa.

Recent and Upcoming Presentations at Scientific Conferences

Berge, P. A., 2001, Modeling Compressional and Shear Wave Velocities of Unconsolidated Sediments in the Vadose Zone: LLNL report UCRL-JC-145245-ABS, submitted to the 2001 Annual Fall Meeting of the American Geophysical Union, to be held Dec. 10-14 in San Francisco, CA.

Berge, P. A., and Bonner, B. P., 2001, Seismic velocities contain information about depth, lithology, fluid content, and microstructure: UCRL-JC-144792-ABS, submitted to the Symposium on the Application of Geophysics to Engineering and Environmental Problems, to be held in Las Vegas, NV, Feb. 10-14, 2002.

Bertete-Aguirre, H., Berge, P. A., and Roberts, J. J., 2001, Imaging Simulated Field Data for Electrical and Mechanical Properties of Shallow Environmental Sites: LLNL report UCRL-JC-145242-ABS, submitted to the 2001 Annual Fall Meeting of the American Geophysical Union, to be held Dec. 10-14 in San Francisco, CA.

Bertete-Aguirre, H., Berge, P. A., and Jeffery J. Roberts, 2001, Using laboratory measurements of electrical and mechanical properties to assist interpretation of field data from shallow geophysical measurements: submitted to the Symposium on the Application of Geophysics to Engineering and Environmental Problems, to be held in Las Vegas, NV, Feb. 10-14, 2002.

Bonner, B. P., Berge, P. A., and Wildenschild, D., Compressional and shear wave velocities for artificial granular media under simulated near surface conditions (expanded abstract): LLNL report UCRL-JC-142935, Technical Program of the Society of Exploration Geophysicists International Exposition and Seventy-First Annual Meeting, Sept. 9-14, 200, San Antonio, TX, Vol. II, 1419-1422.

Toffelmier, D., W. Dufrane, C. Aracne-Ruddle, B. P. Bonner, P. A. Berge, B. Viani, and K. Knauss, 2001, Load Dependence of Ultrasonic Velocities for Sand and Sand / Clay Mixtures: LLNL report UCRL-JC-145264-ABS, submitted to the 2001 Annual Fall Meeting of the American Geophysical Union, to be held Dec. 10-14 in San Francisco, CA.

Patents and Patent Applications

Berryman, J. G., Daily, W. D., Ramirez, A. L., and Roberts, J. J., Using electrical impedance tomography to map subsurface hydraulic conductivity, U. S. Patent No. 6,147,497, November 14, 2000.

Berryman, J. G., Discrimination of porosity and fluid saturation using seismic velocity analysis, U. S. Patent No. 6,269,311, July 31, 2001.

Bonner, B. P., Boro, C., and Hart, D. J., Anti-waveguide for ultrasonic testing of granular media under elevated stress, LLNL Patent disclosure IL-10607, and patent application, DOE Patent Docket No. S-94182, October 28, 1999.

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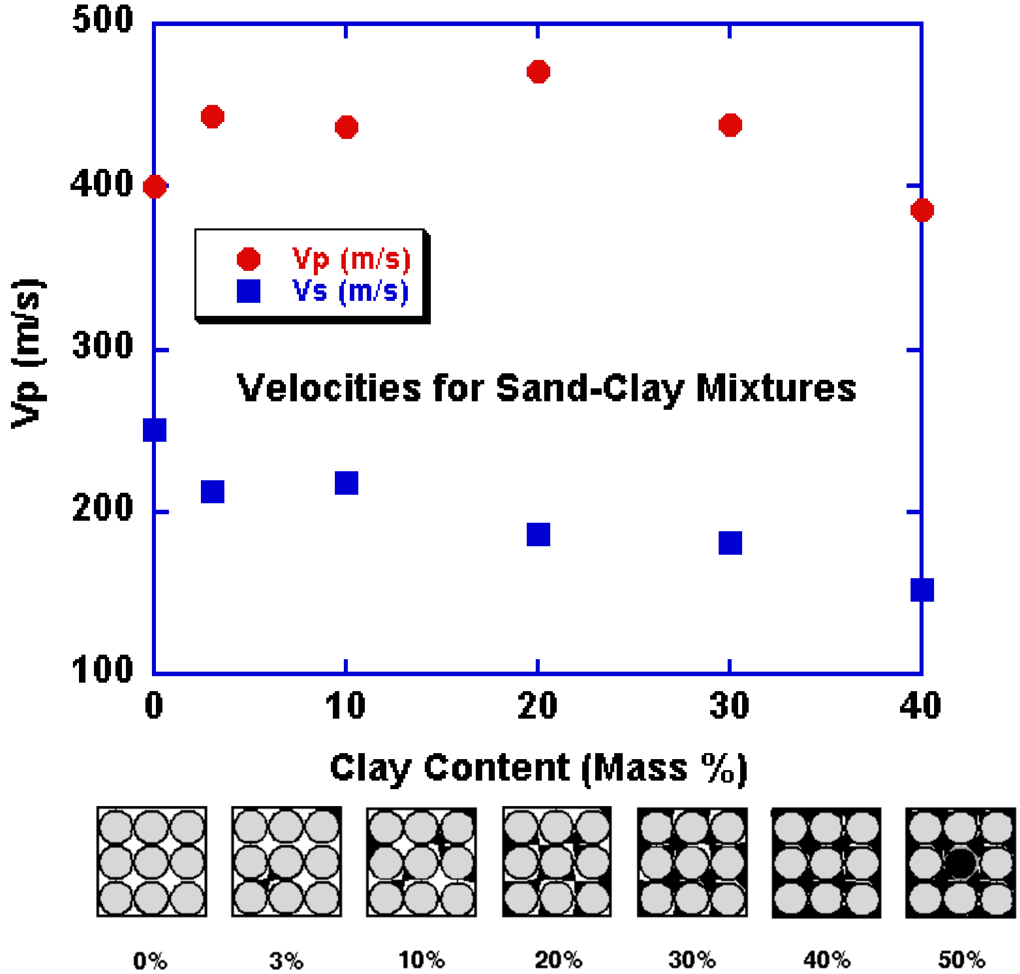
Figure 1



Velocities for Sand-Clay Mixtures
Vp (m/s)
Vs (m/s)
500
400
300
200
100
0
10
20
30
40
Clay Content (Mass %)
0%
3%
10%
20%
30%
40%
50%

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